Absorption lines from magnetically-driven winds in X-ray binaries

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\begin{abstract}
Context. High resolution X-ray spectra of black hole X-ray binaries (BHBs) show blueshifted absorption lines suggesting presence of outflowing winds. Further, observations show that the disk winds are equatorial and they occur in the Softer (disk-dominated) states of the outburst and are less prominent or absent in the Harder (power-law dominated) states.

Aims. We want to test if the self-similar magneto-hydrodynamic (MHD) accretion-ejection models can explain the observational results for accretion disk winds in BHBs. In our models, the density at the base of the outflow from the accretion disk is not a free parameter. This mass loading is determined by solving the full set of dynamical MHD equations without neglecting any physical term. Thus the physical properties of the outflow depend on and are controlled by the global structure of the disk.

Methods. Different MHD solutions were generated for different values of (a) the disk aspect ratio ($e$) and (b) the and ejection efficiency ($p$). We also generate two kinds of MHD solutions depending on the absence (cold solution) or presence (warm solution) of heating at the disk surface. Warm solutions can have large ($>0.1$) values of $p$ which would imply larger wind mass loading at the base of the outflow. We use each of these MHD solutions to predict the physical parameters (e.g. distance density, velocity, magnetic field etc.) of an outflow. We have put limits on the ionization parameter ($\xi$), column density and timescales, motivated by observational results. Further constraints were derived for the allowed values of $\xi$ from thermodynamic instability considerations, particularly for the Hard SED. These physical constraints were imposed on each of these outflows to select regions within it, which are consistent with the observed winds.

Results. The cold MHD solutions are found to be inadequate to account for winds due to their low ejection efficiency. On the contrary, warm solutions can have sufficiently high values of $p(\geq0.1)$ which is required to explain the observed physical quantities in the wind. The heating (required at the disk surface for the warm solutions) could be due to the illumination which would be more efficient in the Soft state. Thus it may be difficult to have warm solutions in Hard states. In addition, from our thermodynamic equilibrium curve analysis, we found that in the Hard state a range of $\xi$ is unstable. This additional constrain makes it impossible to have any wind at all, in the Hard state.

Conclusions. Our results would suggest that a thermo-magnetic process is required to explain winds in BHBs. We could explain the observed trends - that the winds are equatorial and that they are observable in the Soft states (and not expected in the Hard state) of the BHB outbursts. It is possible that a spectral state transition, Hard-to-Soft, occurs at the innermost disk regions that triggers the illumination and hence existence of a warm solution in the outer regions of the accretion disks ($R_{SPH} \geq 5 \times 10^3 r_g$) which, in turn, favours the production of winds.

Key words. Resolved and unresolved aources as a function of wavelength - X-rays: binaries; Stars - stars: black holes, winds, outflows; Physical Data and Processes - accretion, accretion disks, magnetohydrodynamics (MHD), atomic process
\end{abstract}

1. Introduction

The launch of Chandra and XMM-Newton, revealed blueshifted absorption lines in the high resolution X-ray spectra of stellar mass black holes in binaries (BHBs). These are signatures of winds from the accretion disk around the black hole. The velocity and ionization state of the gas, interpreted from the absorption lines, vary from object to object and from observation to observation. In most cases, only H- and He-like Fe ions are detected (e.g Lee et al. 2002, Neilsen & Lee 2009 for GRS 1915+105, Miller et al. 2004 for GX 339-4, Miller et al. 2006 for H1743-322 and King et al. 2012 for IGR J17091-3624). In some of the objects however, a wider range of ions is seen from O through Fe (e.g. Ueda et al. 2009 for GRS 1915+105, Miller et al. 2008; Kallman et al. 2009 for GRO J1655–40). The variations in the wind properties seem to indicate variations in the temperature, pressure and density of the gas from one object to another. Further, even in the same object, the winds seem to have variations depending on the accretion state of the black hole.

Both spectral and timing observations of most BHBs show common behaviour patterns centered around a few states of accretion. The spectral energy distributions (SEDs) corresponding to the different states have varying degree of contribution from the accretion disk and the non-thermal power-law components. The X-ray studies of BHB show that winds are not present in all states. It has been shown by several authors that the absorp-
osition lines are more prominent in the Softer (accretion disk dominated) states (Miller et al. 2008; Neilsen & Lee 2009; Blum et al. 2010; Ponti et al. 2012). For some objects, the reason for such changes is attributed to changes in the photoionizing flux (e.g. Miller et al. 2012, in the case of H1743-322). However, the alternative explanation of 'changes in the driving mechanism' is of greater relevance to this paper.

The observable properties of the accretion disk winds are often used to infer the driving mechanism of the winds (Lee et al. 2002; Ueda et al. 2009, 2010; Neilsen et al. 2011; Neilsen & Homan 2012). Hence the variation or disappearance of the wind through the various states of the BHB, has been interpreted as variation in the driving mechanism of the wind. A good example is the case of GRO J1655-40. A well known Chandra observation of GRO J1655-40 (Miller et al. 2006, 2008; Kahnman et al. 2009), showed a rich absorption line spectrum from OVIII - NiXXVI, and led the authors to conclude for magnetic driving mechanism for the wind. Neilsen & Homan (2012) analysed the data from another observation from 3 weeks later, for the same source, and found absorption by Fe XXVI only. They argue that such a change cannot be due to variation in photoionization flux only and suggest that variable thermal pressure and magnetic fields may be important in driving long-term changes in the wind in GRO J1655-40.

To get a consolidated picture of these systems, it is necessary to understand the relation between the accretion states of the BHBs and the driving mechanisms of the winds. In this paper we investigate the magnetohydrodynamic (hereafter MHD) solutions as driving mechanisms for winds from the accretion disks around BHBs - cold solutions from Ferreira (1997, hereafter F97) and warm solutions from Casse & Ferreira (2000b) and Ferreira (2004). To understand the basic motivation of the MHD solutions used to model the winds, throughout this paper, it is important to discuss the distinction between winds and jets from accretion disks. Observationally, jets are usually described as collimated, fast (mildly relativistic) outflows detected or directly imaged in radio wavelengths. On the other hand, winds are detected as absorption features, showing speeds of a few thousand km s⁻¹. However, on the theoretical side, both are outflows launched from the accretion disk surface due to magnetic and/or thermal/radiative effects. The power carried by these outflows is, ultimately, a fraction of the released accretion power. Hence, although observationally distinct, theoretically, it is not simple to distinguish between the two. One way to make a clear theoretical distinction between these two outflows is to look at the magnetization σ at the disk surface, namely the ratio of the MHD Poynting flux to the sum of the thermal energy flux and the kinetic energy flux. Jets would have σ > 1, a high magnetization translating into both large asymptotic speeds and (magnetic) self-confinement. On the contrary, winds would be much less magnetized (σ < 1) with much lower asymptotic speeds and the confinement (if any) will come only from the external medium.

MHD solutions have been used by other authors to address outflows in various systems. Of particular relevance to this paper are the works presented by Fukumura et al. (2010a,b, 2014, 2015). Based on the self-similar Contopoulos & Lovelace (1994) MHD models of outflowing material, the aforementioned papers have already argued in favour of large scale magnetocentrifugally driven winds in active galactic nuclei (AGN - galaxies which host actively mass accreting super-massive, $M_{\text{BH}} > 10^6 M_\odot$, black holes at their centres). Their analysis shows that such models can account for the observed warm absorbers and ultra-fast outflows seen as absorption lines in high resolution X-ray spectra of AGN. They have also attempted to explain the broad absorption lines (seen in high resolution ultraviolet spectra of AGN) using the same MHD wind models. Note however, that the Contopoulos & Lovelace (1994) model (which is an extension of the Blandford & Payne 1982 hydromagnetic flows) does not treat the underlying disk. As a consequence, the link between the mass loss in winds and the disk accretion rate is lost and the mass loading at the base of the disk can be (almost) arbitrarily large or small. On the contrary, the MHD models in F97 (and subsequent papers) link the density of the outflowing material to the disk accretion rate.

A consistent theory of MHD outflows from the disk must explain how much matter from the disk is deviated from the radial to the vertical motion, as well as the amount of energy and angular momentum carried away from the disk. This requires a thorough treatment of the resistive disk interior and matching it with the outflowing material using ideal MHD. The only way to solve such an entangled problem is to take into account all dynamical terms, a task that has been done within a self-similar framework in F97.

The F97 MHD solutions have been used in Ferreira et al. (2006) and Petrucci et al. (2010), to describe accretion disks giving rise to jets in the Hard States of BHBs. Winds, on the other hand are seen in the Soft state of the BHBs when radio jets are absent. Using the F97 models we aim to test if the same theoretical framework (which could reproduce jets) can reproduce the observed properties of the winds (ionization parameter, column density, velocity etc.). We shall further, look into the parameter space of the theoretical models to distinguish between the Soft accretion states, when the wind is observed and the Harder states when the absorption lines from the wind is not observed.

2. The MHD accretion disk wind solutions

2.1. General properties

We use the F97 solutions describing steady-state, axisymmetric solutions under the following two conditions:

1. A large scale magnetic field of bipolar topology is assumed to thread the accretion disk. The strength of the required vertical magnetic field component is obtained as a result of the solution (Ferreira 1995).

2. Some anomalous turbulent resistivity is at work, allowing the plasma to diffuse through the field lines inside the disk.

For a set of disk parameters, the solutions are computed from the disk midplane to the asymptotic regime of outflowing material becoming, first, super slow-magnetosonic, then, Alfvénic and finally, fast-magnetosonic. All solutions that will be discussed in this paper, have this same asymptotic behavior which corresponds to the following physical scenario: after an opening of the radius of the outflow, leading to a very efficient acceleration of the plasma, the outflow undergoes a refocusing towards the axis (recollimation). The solutions are then, mathematically terminated (see F97 for more details). Physically speaking however, the outflowing plasma will most probably undergo an oblique shock (which is independent of the assumption concerning the thermal state of the magnetic surfaces) after the recollimation happens. However, theoretically accounting for the oblique shock is beyond the scope of this paper. Thus, in this paper we rely on those solutions only, which cross their Alfvén surfaces before recollimating (i.e. before the solutions have to be mathematically terminated).
2.2. Model parameters

The rigorous mathematical details of how the isothermal MHD solutions for the accretion disk outflow are obtained are given in the aforementioned papers and we refrain from repeating them here. In this section, we focus on describing the two parameters that affect the density \( n^+ \) of the outflowing material at a given radius \( r \) in the disk.

Because of ejection, the disk accretion rate varies with the radius even in a steady state, namely \( \dot{M}_{\text{acc}} \propto r^p \). This radial exponent, \( p \) (labelled \( \xi \) in F97, Ferreira et al. 2006; Petrucci et al., 2010, etc.) is very important since it measures the local ejection efficiency. The larger the exponent, the more massive and slower is the outflow. Mass conservation writes

\[
\frac{2dM_{\text{jet}}}{dr} = 4\pi r^p u^{+}_e = \frac{dM_{\text{acc}}}{dr} = p \frac{\dot{M}_{\text{acc}}}{r}
\]

\[
n^+ m_p = \rho^+ = \frac{p \dot{M}_{\text{acc}}}{\varepsilon 4\pi \Omega k r^3}
\]

where \( m_p \) is the proton mass and the superscript "+" stands for the height where the flow velocity becomes sonic, namely \( u^+_e = C_s = \Omega k h = \varepsilon V_K \). Here, \( V_K = \Omega k r = \sqrt{G M_{\text{BH}}/r} \) (\( G \): gravitational constant) is the keplerian speed and

\[
\varepsilon = \frac{h}{r}
\]

is the disk aspect ratio, where \( h(r) \) is the vertical scale height at the cylindrical radius \( r \). It can thus be seen that the wind density, a crucial quantity when studying absorption features, is mostly dependent on \( p \) and \( \varepsilon \) for a given disk accretion rate \( \dot{M}_{\text{acc}} \).

Equation 1 is the fundamental difference between the MHD models used in the aforementioned papers by Fukumura et al. and the ones used in this work. While in the former, the initial wind density \( \rho^+ \) can be “arbitrarily” prescribed i.e. independent of the the underlying disk accretion rate, here it is a result of an accretion-ejection calculation and are determined by \( p \) and \( \varepsilon \). In the Fukumura et al. papers there are two assumptions, put by hand, that determine the physical properties of the outflow.

a) The authors do not use the parameter \( p \). However, comparing the equations for the radial distributions of magnetic field \( (B_s \propto r^{p-2}) \) of the outflow, we can get the relation \( q = \frac{3}{2} + \frac{p}{2} \) (Ferreira 1993). Note that \( q \) is not any parameter related to the accretion disk, but an index related to the outflow. The Fukumura et al. papers discuss the two cases of \( q = 1 \) and \( q = 3/4 \), but for modelling the AGN winds they use the former, which would correspond to \( p = 0.5 \). The choice of \( q = 1 \) was to ensure that the density in the outflow followed \( n \propto r^p \) with \( \alpha = 2q - 3 = 1 \), as suggested by observations.

b) The density at the launching point of the wind is prescribed by a parameter \( \eta_W \) which is the ratio of the mass outflow rate to the disk accretion rate. Note that the authors use a constant value \( \eta_W = 0.5 \), independent of \( q \). These preassigned values for the parameters defining the outflow and the lack of any connection to the accretion process, fosters a sense of "physical arbitrariness". To achieve such a high value of \( \eta_W \), an extra process (other than magneto-hydrodynamic acceleration) must be acting within the resistive disk (this will be discussed later in Section 5 in the context of “Warm” models).

In the MHD models used in this paper the value of the exponent \( p \) influences the extent of magnetisation in the outflow. This is another way in which the ejection index relates the accretion process and the outflow properties. In a non-relativistic framework the ratio of the MHD Poynting flux to the kinetic energy flux at the disk surface is

\[
\sigma^+ = \frac{1}{p} \left( \frac{\Lambda}{1 + \Lambda} \right)
\]

(F97, Casse & Ferreira 2000a) where \( \Lambda \) is the ratio of the torque due to the outflow to the turbulent torque (usually referred to as the viscous torque). The torque due to the outflow transfers the disk angular momentum to the outflowing material whereas the turbulent torque provides an outward radial transport within the disk. Smaller the value of \( p \), larger is the energy per unit mass in the outflow. A magnetically dominated self-confined outflow requires \( \sigma^+ \gtrsim 1 \). The F97 outflow models have been obtained in the limit \( \Lambda \to \infty \) so that the self-confined outflows carry away all the disk angular momentum and thereby rotational energy with \( \sigma^+ \simeq 1/p \gg 1 \). The outflow material reaches the maximum asymptotic poloidal speed \( V_{\text{max}} \sim V_K(r_o)^{p^{-1/2}} \), where \( r_o \) is the anchoring radius of the magnetic field line.

Figure 1 shows the \( p - \varepsilon \) parameter space of super-Alfvenic MHD solutions obtained by F97 with cold, isothermal magnetic surfaces. It can be seen that under these assumptions it is impossible to achieve high values of \( p \gtrsim 0.1 \). Such a limit on the value of \( p \) does not improve even if the magnetic surfaces are changed to be adiabatic, as long as the outflowing material remains cold (Casse & Ferreira 2000a). The outflow is cold when its enthalpy is negligible when compared to the magnetic energy, which is always verified in near Keplerian accretion disks. However, the warming up of the outflowing material could occur if some additional heat deposition becomes active at the disk surface layers (through illumination for instance, or enhanced turbulent dissipation at the base of the corona). In that case, larger values of \( p \) up to \( \sim 0.45 \) have been reported (Casse & Ferreira 2000b; Ferreira 2004). We will examine the cold outflows in Section 4 and the “warm outflows” in Section 5.

2.3. The scaling relationships

For the MHD outflow (with given \( \varepsilon \) and \( p \)) emitted from the accretion disk settled around a black hole, the important physical
quantities are given at any cylindrical (r,z) by

\[ n(r, z) = \frac{m}{\sigma_T r_g} \left( \frac{r}{r_g} \right)^{p-3/2} f_0(y) \]  

(4)

\[ v_i(r, z) = c \left( \frac{r}{r_g} \right)^{-1/2} f_0(y) \]  

(5)

\[ B_i(r, z) = \left( \frac{\mu_i m_p c}{\sigma_T r_g} \right) \frac{1}{2} \left( \frac{r}{r_g} \right)^{-(3+\nu)/2} f_0(y) \]  

(6)

\[ \tau_{dyn}(r) = \frac{2\pi r_0}{c} \left( \frac{r}{r_g} \right)^{3/2} f_2(y) \]  

(7)

where \( \sigma_T \) is the Thomson cross section, \( c \) the speed of light, \( r_g = GM_{BH}/c^2 \) is the gravitational radius, \( \mu_i \) the vacuum magnetic permeability, \( y = z/r \) the self-similar variable and the functions \( f_x(y) \) are provided by the solution of the full set of MHD equations. In the above expressions, \( n \) is the proton number density and we consider it to be \( \sim n_B \) (the Hydrogen number density); \( v_i \) (or \( B_i \)) is any component of the velocity (or magnetic field) and \( \tau_{dyn} = 1/dnV \) (where \( V \) is the plasma velocity) is a measure of the dynamical time in the flow. The normalized disk accretion rate used in Equation 4 is defined by

\[ \dot{m} = \frac{M_{acc}(r_g) c^2}{L_{Edd}} \]

where \( L_{Edd} \) is the Eddington luminosity.

Note that we are using a steady state assumption for the accretion disk of a BHB i.e. the variation of the accretion rate with the radius is assumed to be the same for the entire disk (same \( p \) and same normalization). This assumption is maintained from the innermost regions (a few \( r_g \)) to the outer part of the disk where the disk wind becomes relevant (between \( 10^{-4} - 10^{-3} r_g \)). We acknowledge that this is a simplistic picture since BHBs are outbursting systems where the accretion rate is obviously varying. So the accretion rate of the outer part of disk could be significantly different from the one in the inner part. Taking this effect into account would however, require considering a detailed time evolution of the accretion mechanism through the different stages of the outburst which is far beyond the scope of this paper. Hence we proceed forward to perform our calculations, within the aforementioned scientific framework.

3. Observational constrains

3.1. The spectral energy distribution for the Soft and the Hard state

The SED of BHBs usually comprises of two components - (1) a thermal component and (2) a non thermal power-law component with a photon spectrum \( N(E) \propto E^{-1} \) (Remillard & McClintock 2006). The thermal component is believed to be the radiation from the inner accretion disk around the black hole, and is conventionally modeled with a multi-temperature blackbody often showing a characteristic temperature \( T_{in} \) near 1 keV. During their outbursts the BHBs transition through different states where the SED shows varying degrees of contribution from the aforementioned components. The state where the radiation from the inner accretion disk dominates and contributes more than 75% of the 2-20 keV flux, is fiducially called the Soft state (Remillard & McClintock 2006). On the other hand the fiducial Hard state is one when the non thermal power-law contributes more than 80% of the 2-20 keV flux (Remillard & McClintock 2006). For any given BHB, the accretion disk usually appears to be fainter and cooler in this Hard power-law state than it is in the Soft thermal state.

The radiation from a thin accretion disk may be modeled as the sum of local blackbodies emitted at different radii and the temperature of the innermost annulus (with radius \( r_m \)) of accreted matter can be calculated using

\[ T(r_m) = 6.3 \times 10^8 \left( \dot{m}_{SED} \right)^{1/3} \left( \frac{M_{BH}}{10^8 M_\odot} \right)^{-1/3} \left( \frac{r_m}{2 r_g} \right)^{-1/2} \]  

(8)

(Peterson 1997; Frank, King & Raine 2002) where \( \dot{m}_{SED} \) is a parameter representing normalised accretion rate. A standard model for emission from a thin accretion disk is available as diskbb, the normalisation, is decided by

\[ F_{disk}(\nu) = \frac{\dot{m}_{SED}}{\dot{m}_{disk}} \left( \frac{D}{10 \text{kpc}} \right)^2 \cos \theta \]  

(9)

\[ f(\nu) = f_{disk}(\nu) + [A_p \nu^{-\alpha}] \exp^{-\nu/\nu_m} \]  

(10)

to account for the full SED.

We follow the prescription given in Remillard & McClintock (2006) to choose appropriate values of the relevant parameters to derive the two representative SEDs for a black hole of \( 10 M_\odot \) for which \( r_g = 1.5 \times 10^8 \) cm. We choose \( \dot{m}_{SED} = 0.03 \), and \( \theta = 30^\circ \).

\footnote{http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/}
• **Soft state** (Figure 2 solid red curve): In the Soft state the accretion disk extends all the way to \( r_{in} = 3R_g = 6r_g \). Thus \( T(r_g) = 0.56 \text{ keV} \). The power-law has \( \Gamma = 2.5 \) and \( A_{pl} \) is chosen in such a way that the 2-20 keV disk flux contribution \( f_2 = 0.8 \).

• **Hard state** (Figure 2 dotted-and-dashed black curve): With \( r_{in} = 6R_g = 12r_g \) we generate a cooler disk with \( T(r_g) = 0.33 \text{ keV} \). The power-law is dominant in this state with \( \Gamma = 1.8 \) and \( f_2 = 0.2 \).

For each of the SEDs defined above, we use a high energy exponential cut-off (Equation 10) to insert a break in the power-law. In Equation 10 \( \nu_{max} \) is chosen in such a way that there is a break in the power-law at 100 keV.

For a 10\( M_\odot \) black hole, the Eddington luminosity \( L_{Edd} \) is \( 1.23 \times 10^{39} \text{ erg s}^{-1} \). Using the aforementioned fiducial SEDs, we can derive the luminosity \( L_{rad} \) in the energy range 0.2 to 20 keV, and then the observational accretion rate \( \dot{m}_{obs} \).

\[
\dot{m}_{obs} = \frac{L_{rad}}{L_{Edd}}
\]

\( \dot{m}_{obs} = 0.14 \) using the Soft SED and is equal to 0.07 while using the Hard SED. Thus for simplicity we assume \( \dot{m}_{obs} = 0.1 \) for the rest of this paper.

It is important to note here, the distinction between the disk accretion rate \( \dot{m} \) (Equations 4 and ??) mentioned above, and the observed accretion rate \( \dot{m}_{obs} \), which is more commonly used in the literature. One can define,

\[
\dot{m} = \frac{2 \dot{m}_{obs}}{\eta_{acc} \eta_{rad}}
\]

where the factor 2 is due to the assumption that we see only one of the two surfaces of the disk.

The accretion efficiency \( \eta_{acc} = r_g/2r_{in} \) depends mostly on the black hole spin. For the sake of simplicity, we choose the Schwarzschild black hole, so that \( \eta_{acc} \approx 1/12 \), both in Soft and Hard state.

The radiative efficiency, \( \eta_{rad} = 1 \) if the inner accretion flow is radiatively efficient i.e. it radiates away all the power released due to accretion. This is the case for a standard (i.e. geometrically thin, optically thick) accretion disk and is satisfied in the Soft state when the standard accretion disk extends all the way up to \( r_{in} = 6r_g \). Thus \( \dot{m} = 24\dot{m}_{obs} = 2.4 \). We acknowledge that \( \eta_{rad} \) can be expected to be \( < 1 \) in the Hard state because the interior most parts of the accretion disk may be more complex. In the Hard state, part of the accretion power could be advected and not radiated (like in accretion dominated accretion flow, ADAF), or ejected (like in Jet Emitting Disks, Ferreira et al. 2006). Instead of going into detailed calculations of such kind of accretion disks, we accounted for the resultant modifications in the Hard SED, by merely increasing the standard accretion disk radius \( r_{in} \) to 12\( r_g \) in (Equations 8 and 9, keeping in mind that the inner part of the flow could be filled by a different, radiatively less efficient, accretion flow. But, \( \dot{m}_{obs, Hard} \) is slightly smaller (0.07) than \( \dot{m}_{obs, Soft} \) (0.14). Hence, for the sake of simplicity, we assume that the ratio \( \dot{m}_{obs}/\eta_{rad} \) remains the same for the Soft and the Hard states. Thus the same value of \( \dot{m} = 2.4 \) can be retained for the Hard state.

### 3.2. Definition of the detectable wind

The MHD solutions can be used to predict the presence of outflowing material over a wide range of distances. For any given solution, this outflowing material spans large ranges in physical parameters like ionization parameter, density, column density, velocity and timescales. Only part of this outflow will be detectable through absorption lines - we refer to this part as the “detectable wind”.

Ionization parameter is one of the key physical parameters in determining which region of the outflow can form a wind. There are several forms of ionization parameter in the literature. In this paper we use the definition, more commonly used by X-ray high resolution spectroscopists, namely \( \xi = L_{ion}/(n_H R_{ph}^2) \) (Tarter et al. 1969), where \( L_{ion} \) is the luminosity of the ionizing light in...
the energy range 1 - 1000 Rydberg (1 Rydberg = 13.6 eV) and \( n_T \) is the density of the gas located at a distance of \( R_{gal} \). We assume that at any given point within the flow, the gas is getting illuminated by light from a central point source. This simplified approach is not a problem unless the wind is located at distances very close to the black hole (\( \leq 100r_g \)). The SEDs for this radiation has been discussed in the previous Section 3.1.

For detecting the presence of ionized gas, we need to evaluate if the ionization parameter of the gas is thermodynamically stable. Any stable photoionised gas will lie on the thermal equilibrium curve or ‘stability’ curve of log \( T \) vs log(\( \xi/T \)) (Figure 3). This curve is often used to understand the structure of absorbing gas in AGN (Chakravorty et al. 2008, 2009, 2012, and references therein) and BHBs (Chakravorty et al. 2013; Higginbottom & Proga 2015). If the gas is located (in the \( \xi = T \) space) on a part of the curve with negative slope then the system is considered thermodynamically unstable because any perturbation (in temperature and pressure) would lead to runaway heating or cooling. Gas lying on the part of the curve with positive slope, on the other hand, is thermodynamically stable to perturbations and hence likely to be detected when they will cause absorption lines in the spectrum.

With C08 we generated stability curves using both the Soft and the Hard SEDs as the ionizing continuum. For the simulation of these curves we assumed the gas to have solar metallicity, \( n_T = 10^{10} \text{ cm}^{-3} \) and \( N_H = 10^{23} \text{ cm}^{-2} \). Assuming these representative average values of \( n_T \) and \( N_H \) are reasonable because the stability curves remain invariant when these two parameters are varied over a wide range spanning several decades (see Chakravorty et al. 2013, for details). The Soft stability curve (solid red line in Figure 3) has no unstable region, whereas the Hard one (dotted-and-dashed black line) has a distinct region of thermodynamic instability which is marked by the thick grey line. This part of the curve corresponds to 3.4 < log \( \xi < 4.1 \). Thus, this range of ionization parameter has to be considered undetectable, when we are using the Hard SED as the source of ionising light.

Literature survey shows that it is usually absorption lines from H- and He-like Fe ions that are detected (e.g Lee et al. 2002, Neilson & Lee 2009, Miller et al. 2004, Miller et al. 2006, King et al. 2012). In fact, it is the absorption line from FeXXVI that is most commonly cited as observed. A very important compilation of detected winds in BHBs was presented in (Ponti et al. 2012), and this paper also, concentrates the discussion around the line from FeXXVI. Hence we choose the presence of the ion FeXXVI as a proxy for detectable winds. The probability of presence of a ion is measured by its ion fraction. The ion fraction \( I(X^{+}) \) of the \( X^{+} \) ion is the fraction of the total number of atoms of the element \( X \) which are in the \( j \)th state of ionization. Thus,

\[
I(X^{+}) = \frac{N(X^{+})}{f(X)N_{H}}
\]

where \( N(X^{+}) \) is the column density of the \( X^{+} \) ion and \( f(X) = n(X)/n_T \) is the ratio of the number density of the element \( X \) to that of hydrogen. Figure 4 shows the ion fraction of FeXXVI calculated using version C08.00 of CLOUDY2 (hereafter C08, Ferland et al. 1998). The ion fractions are of course, different based on whether the Soft or the Hard SED has been used as the source of ionization for the absorbing gas. The value of log \( \xi \) where the presence of FeXXVI is maximised, changes from 4.05 for the Hard state, by ~ 0.8 dex, to 4.86 for the Soft state.

In the light of all the above mentioned observational constraints, we will impose the following physical constraints on the MHD outflows (in Sections 4 and 5) to locate the detectable wind region within them:

- In order to be defined as an outflow, the material needs to have positive velocity along the vertical axis (\( z_{bol} \)).
- Over-ionized gas cannot cause any absorption and hence cannot be detected. Thus to be observable via FeXXVI absorption lines we constrain the material to have an upper limit for its ionization parameter. We imposed that \( \xi \leq 10^{4.86} \text{ erg cm} \) (peak of FeXXVI ion fraction) for the Soft state. The ion fraction of FeXXVI peaks at \( \xi = 10^{4.4} \text{ erg cm} \) for the Hard state, but this value is within the thermodynamically unstable range. Hence for the Hard state, the constraint is \( \xi \leq 10^{4.4} \text{ erg cm} \), the value below which the thermal equilibrium curve is stable.
- The wind cannot be Compton thick and hence we impose that the integrated column density along the line of sight satisfies \( N_H < 10^{24} \text{ cm}^{-2} \).

3.3. Finding the detectable wind within the MHD outflow

In this subsection we demonstrate how we choose the part of the MHD outflow which will be detectable through absorption lines of FeXXVI. For the demonstration we use the MHD solution with \( e = 0.001 \) and \( p = 0.04 \) which is illuminated by the Soft SED. Hereafter we will refer to this set of parameters as the “Best Cold Set”. For the purpose of discussion in this subsection, we will work with the Soft SED only, but in subsequent sections additional calculations will be carried out for the scenario where the MHD outflow is illuminated by the Hard SED.

Figure 5 shows the ionization parameter distribution and the density distribution of the outflow due to the “Best Cold Set”. The solid black lines threading through the distribution shows the magnetic field lines along which material is outflowing. The MHD solutions are mathematically self-similar in nature, which essentially means that we can propagate the solutions infinitely. However we have restricted the last streamline to be anchored at \( r_g = 10^3 r_g \). In Section 3.2 we listed the three required physical conditions for detectable wind. We use those physical constraints on the ‘Best Cold Set’ and get the yellow ‘wedge’ region in Figure 5. The top panel of the figure is a global view, which shows the entire span of the MHD solution that has been evaluated. However we see that the wind is detected only from the outer parts of the flow with log \( R_{gal} \text{wind}/r_g \geq 5.4 \). The lowest and highest equatorial angle (\( \iota \)) of the line of sight are clearly marked for the wind region (in both panels). The observer will have to view the BHB within this angular range to be able to detect the wind. The wind is equatorial, for the ‘Best Cold Set’, not extending beyond \( \iota = 26.9^\circ \).

In the lower panel of Figure 5 we use a linear (but normalised by \( 10^3 r_g \)) scale for \( r_{gal} \) and \( z_{bol} \), which renders us a close up view of the wind region within the solution. The labelled dashed black lines are the iso-contours for the number density log \( n_{H} \text{ cm}^{-3} \). We have checked that the velocities \( v_{obs} \) within this region fall in the range \( 10^2 - 10^3 \text{ km s}^{-1} \).

To ensure that the wind is in thermal equilibrium, it is important to compare the various physical timescales. We used C08 to evaluate the cooling time scales at each point within the wind region of the solution. CLOUDY assumes that atomic processes (including photoionization and recombination cooling) occur on timescales that are much faster than other changes in the system, so that atomic rates have had time to become “time-steady”. These atomic processes, in addition to some other continuum processes like Comptonization and Bremsstrahlung, are respon-
Fig. 5. **Top Panel:** The distribution of the 'Best Cold Set' in the logarithmic plane of the radial ($r_\omega$) and vertical ($z_\omega$) distance (in cylindrical coordinates) from the black hole. The distances are also expressed in terms of the gravitational radius $r_g$ (top axis), which is $1.5 \times 10^6$ cm for a $10M_\odot$ black hole. The colour gradient informs about the $\xi$ distribution of the flow. The solid black lines threading through the distribution show some of the magnetic field lines along which material is outflowing. The Alfvén surface corresponding to the solution is also marked and labelled. The yellow wedge highlights the wind part of the flow - this material is optically thin with $N_H < 10^{24}$ cm$^{-3}$ and has sufficiently low ionization parameter ($\xi < 10^{4.86}$ erg cm) to cause FeXXVI absorption lines. The angular extent of the wind is also clearly marked, where $i$ is the equatorial angle.

**Bottom Panel:** A close up view of the wind region. The distances are expressed in linear scale, but normalised to $10^7 r_g$. The dashed lines show the iso-contours of $n_H$, while the associated labels denote the value of $\log n_H$(cm$^{-3}$).
sible for heating and cooling the gas. Whether the atomic processes dominate over the continuum processes is determined by the ionization state and/or the temperature of the gas. For photoionized wind we expect the atomic processes to dominate. However, one way to make sure that the gas satisfies the time-steady condition (which is assumed by CLOUDY) is to check the CLOUDY computed cooling time scale against the dynamical time scales from our physical MHD models. CLOUDY defines the cooling time scale as the time needed to lose half of the heat generated in the gas due to various atomic and continuum processes. Thus thermal equilibrium is also ensured as long as the cooling time scale is smaller than the dynamical time scale $t_{\text{dyn}}$ - which was found to be true within the wind region of the outflow.

This same method of finding the wind, and the associated physical conditions is used for all the cold MHD solutions considered in this paper. In the subsequent sections we will vary the MHD solutions (i.e. $c$ and $p$) and investigate the results using both the Soft and Hard SEDs.

4. The cold MHD solutions

4.1. Effect of variation of the parameters of the MHD flow

Here we aim to find which of the two parameters $c$ and $p$ is more influential in producing the wind. The value of $p$ and $c$ decides the density of material at the launching point of our magnetohydrodynamic outflow (Equation 1). The extent of magnetisation in the outflow is also dependant on $p$ (Section 2). It is these two parameters that links the density and other physical properties of the outflow with the accretion disk. Since a particular pair of $p$ and $c$ will result in a unique MHD solution, we can generate different MHD solutions, by changing the values of $p$ and $c$. On each of these solutions, we perform the methods described in the previous Section 3.3 and investigate the wind part of the outflow.

To judge the influence of $p$ and $c$, in a quantitative way, we compare some physically relevant parameters of the wind. For observers, one important set of wind parameters are the distance, density and velocity of the point of the wind closest to the black hole. Hereafter we shall call this point as the ‘closest wind point’. Another quantity of interest would be the predicted minimum and maximum angles (of the line of sight) within which the wind can be detected. We conduct this exercise using both the SEDs - Soft and Hard. The results are plotted in Figure 6.

The exact value of these quantities should not be considered very rigorously, because the value is decided by the various constraints that we have applied. It is more important to note the changes in these quantities as $c$ and $p$ vary. The relative changes should be used to assess how variations in $c$ and $p$ increase the possibilities of detecting the wind.

4.1.1. Variation of the disk aspect ratio $\epsilon$

For the closest wind point, we plot $R_{\text{sph, loud}}$ versus the value of $\epsilon$ of the MHD solution, in panel A of Figure 6. Further, $n_{\text{obs}}$ and $v_{\text{obs}}$ for this point are labelled. Using the Soft SED, the closest wind point reaches closer to the black hole by a factor of 1.06 as $\epsilon$ increases from 0.001 to 0.01, and then by a farther factor of 1.14 as $\epsilon$ increases to 0.1. The density at the closest point is $n_{\text{obs,max}} = 10^9.37\,\text{cm}^{-3}$, for $\epsilon = 0.001$. Note that for any given solution, the density at the closest point is the maximum attainable density within the wind region, for that particular MHD solution. This maximum attainable density of the wind, increases as $\epsilon$ increases to 0.01 and then to 0.1. However, as a function of $\epsilon$, the variation in this quantity is not very high, but only 0.16 dex. Like density, for a given solution, the velocity at the closest wind point, $v_{\text{obs,max}}$, is the highest that can be attained by the detectable wind. This quantity monotonically decreases by 0.26 dex and then by 0.49 dex as $\epsilon$ increases from 0.001 to 0.01 and then to 0.1. This means, to get winds with higher speed, we need disks with higher aspect ratios.

As $\epsilon$ increases from 0.001 to 0.01 to 0.1. The growth of $R_{\text{sph, loud}}$ drops by a factor of 1.3 as $\epsilon$ changes in these quantities as $\epsilon$ increases from 0.001 to 0.01 to 0.1. The growth of $\Delta = i_{\text{max}} - i_{\text{min}}$ with $\epsilon$ shows that the wind gets broader as the disk aspect ratio increases.

4.1.2. Variation of the ejection index $p$

As $p$ increases, the wind moves closer to the black hole (panel B of Figure 6) - $R_{\text{sph, loud}}$ drops by a factor of 1.3 as $p$ goes from 0.01 to 0.02 and then reduces further by a factor of 1.41 when $p$ is increased to 0.04, while using the Soft SED. The total change in the density of the closest wind point is 0.51 dex as $p$ changes from 0.01 to 0.04. Thus both $R_{\text{sph, loud}}$ and $n_{\text{obs,max}}$ are effected more by the variation in $p$ than by the variation in $\epsilon$ (within the range of these parameters investigated by us). The velocity $v_{\text{obs,max}}$ of the closest point however, varies far less with change in $p$, the total decrease being only 0.24 dex.

As $p$ increases, the wind gets broader as the disk aspect ratio increases. In panel D of Figure 6, as $p$ goes from 0.01 through 0.02 to 0.04, the minimum angle rises from 0.60 through 1.65 to 3.45, a range rather smaller than that caused by the $\epsilon$ variation. $i_{\text{max}}$ goes from 2.27 to 7.89 to 26.9. Thus the growth of $\Delta = i_{\text{max}} - i_{\text{min}}$ is rendered to be higher as a function of increase in $p$, implying a higher probability of detecting a wind when the wind corresponds to higher $p$ values. Since $p$ is the relatively more dominant (compared to $\epsilon$) disk parameter in increasing the density at a given distance, the resultant outflowing material has lower ionisation. This is a favourable influence to cause detectable winds.

4.2. Cold solutions for the Hard state

For the entire range of $\epsilon$ (0.001 - 0.1) and $p$ (0.1 - 0.4) we analysed the MHD solutions illuminated by the Hard SED, as well. Note that for the Hard SED, we have to modify the upper limit of $\xi$ according to the atomic physics and thermodynamic instability considerations (Section 3.2). With the appropriate condition, $\log \xi \leq 3.4$, we could not find any wind portions within the Compton thin part of the outflow, for any of the MHD solutions.

This is a very significant result, because this provides strong support to the observations that BHBs do not have winds in the Hard state. We will discuss this issue further complimented with better quantitative details in Section 6.3.

4.3. The need for Warm MHD solutions

The density reported for most of the observed BHB winds $\geq 10^{11}\,\text{cm}^{-3}$ and the distance estimates place the winds at $\leq 10^{10}\,\text{cm}$ (Schulz & Brandt 2002; Ueda et al. 2004; Kubota et al. 2007; Miller et al. 2008; Kallman et al. 2009). Our analysis in the previous subsections show that $R_{\text{sph, loud}}$ is too high and $n_{\text{obs,max}}$ is too low even for the ‘Best Cold Solution’ to match
observations. The purpose of this section is to understand which parameter of the accretion-ejection process can provide us with a MHD solution capable of explaining observed (or derived) parameters of BHB winds. Studying the effect of the disk parameters gives us a clear indication that increasing the value of the ejection index $p$ favours the probability of detecting winds, as demonstrated by the larger extent of increase in $\Delta \varepsilon$. Further, the increase in $p$ results in two more favourable effects - the closest wind point moves closer to the black hole and causes a higher increase in density.

The above phenomenological tests of the $\varepsilon - p$ space, indicates that a MHD solutions with higher $\varepsilon$, say 0.01, and a high $p \geq 0.04$ would be the better suited to produce detectable winds, comparable to observations. However there are limitations on the $\varepsilon - p$ combination imposed by the physics of the MHD solutions (see Figure 1) and it is not possible to reach larger values of $p$ for the cold solutions with isothermal magnetic surfaces. As shown in Casse & Ferreira (2000b), to get denser outflows with larger $p$, some additional heating needs to take place at the disk upper layers leading to a warming up of the wind. The authors argued that the origin of this extra heating could be due to illumination from an external source. Qualitatively speaking, it can be imagined that in the Soft state, when the disk is present all the way up to the innermost stable orbit, the radiation from the innermost parts provides the illumination to the outer accretion disk resulting in the heating of the upper layers. We can thus think that a spectral state transition in the innermost disk regions could trigger a difference in the outer MHD solution, switching it from a $p \sim 0.01$ cold solution (say) to a “warm” solution with much larger $p$. Let us now investigate in the following section if a warm solution is indeed, much better for producing winds matching observations.

5. Warm MHD solutions

In this section we investigate the properties of the wind as a function of increasing $p$, but for warm MHD solutions. Here we choose to ignore the effect of $\varepsilon$, because in the previous section we found that variation in $\varepsilon$ (over two orders of magnitude) has very little effect on changing the physical quantities of the wind. Further, in the previous sections we found that the wind does not exist for the Hard SED. Hence, we shall conduct the extensive calculations with the Soft SED only. We shall however, discuss winds in the Hard state in Section 6.3 as a part of general discussions.

Self-confined outflows require $\sigma^+ = 1/p$ larger than unity, as pointed out through Equation 3 in Section 2.2. Moreover, the power in the outflow is always a sizable fraction of the mechanical power

$$L_{\text{acc}} = \left[ \frac{GM_{\text{BH}} M_{\text{acc}}(r)}{2r} \right] \frac{\dot{M}_{\text{w}}}{\dot{M}_{\text{acc}}}$$

(released by the accreting material between the inner radius $r_{\text{in}}$ and the outer radius $r_{\text{out}}$). Because $M_{\text{acc}}(r) \propto r^p$ in a disk, launching outflows, one gets $L_{\text{acc}} = 0$ for $p = 1$. This is why, unless there is an external source of energy, $p = 1$ is a maximum limit, and in fact, powerful magnetically driven flows require a much smaller ejection index. To consider what highest value of $p$ should be aimed for, we scout the literature. We find two relevant references, namely,

![Fig. 6.](image-url)
Fig. 7. The ionization parameter distribution for a Warm MHD solution with $\varepsilon = 0.01$ and $p = 0.10$. The yellow region within the outflow is obtained in the same way as in Figure 5. The shaded region (with dotted red lines) is the wind region within such a warm outflow - to obtain this region we used the additional constraint that the cooling timescale of the gas has to be lower than the dynamical time scale. Further, the solid blue line with $i = 38.1^\circ$ is drawn to depict that high density material ($\log n_H \geq 8.0$) in the flow is confined to low equatorial angles.

(a) Casse & Ferreira (2000b) who computed warm MHD accretion-ejection solutions up to $p = 0.456$ to model winds mostly, in young stellar objects and

(b) a series of papers by Fukumura et al. (Fukumura et al. 2010a, b, 2014, 2015), who used a model with $p = 0.5$. Hence while generating the thermo-magnetically driven and magnetically confined outflows, we will limit ourselves to $p \leq 0.5$.

For this paper, we obtain dense warm solutions (with higher values of $p$, i.e. $p \geq 0.04$) through the use of an ad-hoc heating function acting along the flow. This additional heating needs to start within the disk itself, in the resistive MHD layers, in order to cause a larger mass loading at the base of the outflow. However, the heating requires to be maintained for some distance within the outflow too, into the ideal MHD zone. This is necessary in order to help the launching of these dense outflows and tap the thermal energy content instead of the magnetic one (refer to Casse & Ferreira 2000b, for more details). It must therefore be realized that any given “warm solution” from a near Keplerian accretion disk is based on an ad-hoc heating term (the function $Q$ in Casse & Ferreira 2000b).

To ease comparison between various warm models, we use the same shape for the heating function, while playing only with its normalization to increase $p$ (the larger the heat input, the larger the value of $p$, see Figure 2 in Casse & Ferreira 2000b). For $\varepsilon = 0.01$ we could achieve a maximum value of $p = 0.11$ which is already enough for our purpose here. For the purpose of this paper, it is not required to provide the “most massive” (i.e. largest possible $p = 0.5$) solution - it is enough to show general trends. However, we are developing the methods to generate denser MHD solutions with $p = 0.5$ and these solution(s) will be reported in our subsequent publications where we will attempt to model the winds observed in specific outbursts of specific BHBs.

Figure 7 shows the wind for a Warm MHD solution with a rather high $p = 0.10$. The wind (yellow region) spans a much wider range (than even the “Best Cold Solution”) and extends far beyond the Alfvén surface which was not the case for the cold MHD solutions. Hence we introduce an additional constraint derived from timescale considerations. The lower angular limit ($i = 11.7^\circ$) is derived due to the constraints of $\xi$ and $N_H$. Next, we used CLOUDY to calculate the cooling timescales of the gas at each point within the yellow wind region of the outflow. Note that for the timescale calculations using CLOUDY (which are computationally expensive) we have used a much coarser grid of $i$ than that used for other calculations of the MHD solutions. This is sufficient for our purpose here, where a coarse upper limit on $i$ is sufficient. To be consistent with a photoionised wind which is in thermal equilibrium, the cooling timescale needs to be shorter than the dynamical timescale. This timescale condition was satisfied within the yellow region if $i \leq 60^\circ$. Thus the red-dotted shaded region is the resultant detectable wind. However, note that the densest parts of the wind is confined to low equatorial angles. For example, gas with $n_H \geq 10^8 \text{ cm}^{-3}$ will lie below $i = 38.1^\circ$. 

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We investigated warm MHD solutions with a range of values of $p$. In Figure 8 we have plotted the distance of the closest wind point for all those solutions. Each point is also labelled with the respective values of density and velocity. Between the $p = 0.04$ solution and the one with the highest $p = 0.11$ (that we could achieve) $R_{\text{sph,wind}}$ goes closer by a factor of $3.79$ and stands at $7.05 \times 10^7 \, r_g$. The highest density that we could achieve is $\log n_H = 11.1$ and the highest velocity is $\log v_{\text{obs}} = 3.43$. Hereafter we shall refer to the $\varepsilon = 0.01$ and $p = 0.10$ warm MHD solution as the “Best Warm Solution”.

Clearly, warm solutions do a much better job than cold ones, as expected. However, some observational results require the winds to have higher density and lower distance than those produced by the “Best Warm Solution”. In the following section we discuss the possibilities in which we can theoretically achieve more stringent values demanded by observations of some extreme winds.

6. Discussions and Conclusions

6.1. Choice of upper limit of $\xi$

The ionization parameter is the key parameter in defining the wind region within the outflow. Here we discuss (a) the possibility of changing $\xi$ if $\dot{m}$ changes and (b) the effect if the upper limit of $\xi$ is changed.

(a) In the definition of $\xi$, the density $n_H$ in the denominator is proportional to $\dot{m}$ (see Equation 4). In the numerator, $L_{\text{ion}} \propto L_{\text{rad}}$ and we also assume $L_{\text{rad}}$ to be proportional to $\dot{m}$ (see Section 3.1). Hence for a given MHD solution, changing $\dot{m}$ will not change the $\xi$ distribution within the outflow.

In the case of inefficient accretion flow like ADAF, $L_{\text{rad}} \propto \dot{m}^2$, and changes in $\dot{m}$ could have some effects. However, we are considering here, physical scenarios, where the accretion disk is radiatively efficient with $n_{\text{obs}} \sim 0.1$. Hence, accepting $L_{\text{rad}} \propto \dot{m}$ is a reasonable assumption.

(b) We used the limit $\log \xi \leq 4.86$ to define the detectable wind. Note that for the Soft SED, $\log \xi = 4.86$ corresponds to the peak of the ion fraction of FeXXVI (Figure 4). The ion can have significant presence at higher $\xi$. For example, at $\log \xi = 6.0$ FeXXVI is still present, but at $\sim 1/4$ of its peak value. Further, there are other ions (including NiXXVIII) which peak at higher values of $\xi$ (see Figure 4 of Chakravorty et al. 2013). Such ions have been reported in Miller et al. (2008). In fact such ions may be routinely detected in data from the future X-ray telescopes like Astro-H and Athena. It is thus instructive to investigate how the properties of the closest wind point (for a given solution) are modified when the constraint on upper limit of $\log \xi$ is changed.

For the best warm solution we calculated the physical parameters for the closest wind point with a modified upper limit $\log \xi = 6.0$. We find that $R_{\text{sph,wind}}$ decreases by a factor of $93.4$ bringing this point to $9.1 \times 10^2 \, r_g$. The density at this point is $\log n_H = 13.71$ and the velocity is $\log v_{\text{obs}} = 4.28$. Thus we see that the parameters of closest point is sensitively dependant on the choice of the upper limit of $\xi$.

6.2. The need for denser warm solution

From the analysis presented in Section 4.1 and Section 5 it is clear that MHD solutions with larger $p$ favour winds which are closer to the black hole. Even for the densest solution discussed in this paper, with $\varepsilon = 0.01$ and $p = 0.11$, we cannot predict a wind closer than $7.05 \times 10^7 \, r_g$ (for $\log \xi \leq 4.86$) and denser than $\log n_H > 11.07$. However Miller et al. (2008) discussed that the wind in GRO J1655-40 was very dense, where $\log n_H \geq 12$, and hence had to be very close to the black hole at $\sim 10^8 \, r_g$. Thus, to explain such extreme winds, we need denser warm MHD solutions with higher $p$. 

![Fig. 8. Distance (density and velocity) of the closest wind point is (are) plotted (labelled) as a function of $p$ for all the warm MHD solutions that we investigated. $\varepsilon = 0.01$ is constant.](image-url)
Fig. 9. The wind characteristics, when the “Best Warm Solution” is illuminated with a Hard SED. The drastically reduced (compared to Figure 7) yellow region within the outflow is obtained in the same way as in Figures 5 and 7. We can only see a very small portion of this yellow region at $r_{\text{out}}/(10^7 r_g) > 0.8$. The rest of this yellow region is occulted by the pink wedge which represents the part of the outflow which is thermodynamically unstable and has $3.4 \leq \log \xi \leq 4.05$. Note that a small part of this unstable outflow is within the Compton thick region with $\log N_H > 24$ (portions below the line marking the low angle $i = 11.9^\circ$).

In the context of AGN, Fukumura et al. (2010a,b, 2014, 2015) have been able to reproduce the various components of the absorbing gas using MHD outflows which would correspond to $p \approx 0.5$. As discussed in Section 5, we have not been able to reproduce such high values of $p$ and are limited to $p = 0.11$. Our calculations in the previous section shows that as $p$ increased from 0.04 to 0.11 for the warm MHD solution, $R_{\text{shwind}}$ for the closest wind point decreased by a factor of 3.79. Thus a further increase to $p = 0.5$ may take the closest wind point nearer to the black hole by a further factor of $\sim 10$ to $\sim 5 \times 10^3 r_g$. The above hypothetical numbers are assuming an almost linear change in density as $p$ increases. In reality, the progression of the physical quantities in the denser MHD solutions may not be that simple. We shall report the exact calculations in our future publications.

As our analyses stand now, even with denser warm MHD solutions with $p = 0.5$ we do not expect the wind to exist closer than $\sim 5 \times 10^3 r_g$, if $\log \xi < 4.86$. However, note from the discussion in the previous subsection, this distance may be reduced by a factor of $\sim 90$ to few $< 10^3 r_g$ for a modified constraint of $\log \xi < 6.0$. The density and velocity will be increased accordingly. These speculative numbers indicate that indeed the warm MHD outflow models may be able to explain even the most extreme winds observed (Miller et al. 2008; King et al. 2012). The aforementioned speculations strongly indicate to us the kind of MHD solutions that we need to generate to fit observations. However a confirmation of this speculations is beyond the scope of this paper. We will report the exact calculations for the extreme MHD models in our subsequent papers.

6.3. Effect of thermodynamic instability in the Hard state

Conventionally it is assumed that ionized gas cannot be detected if it is thermodynamically unstable. Chakravorty et al. (2013) showed the effect of thermodynamic considerations and found that the equilibrium curve to be unstable for a range of $\xi$ values, but only for the Hard SED. We have conducted stability curve analysis in Section 3.2 and have found similar results - for the Hard SED, the range $3.4 < \log \xi < 4.1$ is thermodynamically unstable. Thus the constraints on $\xi$ have to be modified accordingly, when looking for the wind region within an outflow illuminated by the Hard SED.

In Section 4.2 we have mentioned that with the appropriate restrictions on the $\xi$ value, no wind could be found within the cold MHD outflows. Since the warm solutions result in much broader (than that in cold solutions) wind region, we test if the best warm solution can have a wind with a Hard SED.

Using the value $\log \xi = 4.05$, we get a significant (although reduced from the Soft SED case) wind region. Next, we check the effect of thermodynamic instability. In Figure 9 the pink region shows the part of the outflow which has $\log \xi = 3.4 - 4.05$, a range that is “thermodynamically unstable”. Note that above the $i = 11.9^\circ$ line (which marks the Compton thick limit), this
thermodynamically unstable zone almost completely occults the wind region (in yellow). This implies that in the Hard state, even if a significant region of the outflow is Compton thin and has the correct \( \log \xi \) to produce FeXXVI lines, this same region is also thermodynamically unstable. Hence in the Hard state, we cannot expect to detect the wind.

The results discussed in this subsection assumed that one can have warm solutions in the Hard state. However, warm solutions may be a characteristic of the Soft state only (see next Section 6.4), making it further difficult for a wind detection in Hard state.

Our analysis thus, strongly suggests that winds will not be detected in the Hard state. Hence, we are in agreement with observational results which detect winds only in the Softer states of the outburst (Ponti et al. 2012).

6.4. Soft SED and warm MHD solutions

Photoelectric absorption of X-ray radiation illuminating the accretion disk may be the natural physical explanation for the heat deposit process that is required for the warm MHD solutions. Note that photoelectric absorption is irrelevant at the innermost parts of the accretion flow of an X-ray binary, because the disk is highly ionized in these parts (the disk temperature is expected to be larger than \( \sim 10^5 \text{eV} \) at radius \( < 10^3 r_g \) for a \( 10M_{\odot} \) black hole radiating at \( 0.1 L_{Edd} \)). At larger distances however, the disk is cooler and photoelectric absorption becomes more efficient.

The heat deposition through photoelectric absorption is expected to be much larger in the case of an illuminating Soft SED compared to a Hard one. Indeed in the case of a Soft SED, a large majority of photons have energy below \( \sim 5 \text{keV} \) i.e. in the energy domain where most of the X-ray atomic transitions occur (e.g. Morrison & McCammon 1983). In other words, the spectral transition from a Hard to a Soft SED is naturally consistent with the scenario of increased heat deposition in the upper layers of the outer disk.

It is thus natural to speculate that as the SED transforms from Hard to Soft, the MHD solutions also translates from cold to warm. This speculation will go well with observations, because warm solutions are much more favourable in producing winds.

However, it is difficult to say, at this stage, that such a transition is the sole cause of not having a wind in the Hard state. As we have discussed and shown above, the thermodynamic instability conditions of the Hard state are sufficient to cause non-detection of wind, even for a warm solution.

7. Conclusions

Winds are detected as absorption lines in the high resolution X-ray spectra of black hole binaries. The absorption lines are mostly from H-like and He-like Fe, but some rare observations show lines from other ions. Ponti et al. (2012) have shown that winds are seen in the Soft state of the outburst and never in the canonical Hard states. Further, the strongest winds were observed for objects with high inclination angles, i.e. the winds flow close to the disk surface at low equatorial angles. In this paper we investigated if magneto centrifugal outflows (Ferreira 1997; Casse & Ferreira 2000b) can reproduce the observed winds in terms of the correct range of ionization parameter (\( \xi \)), column density (\( N_\text{H} \)), velocity (\( v_{\text{rad}} \)) and density \( n_H \). The investigations are done as a function of the two key accretion disk parameters - the disk aspect ratio \( \epsilon \) and the radial exponent \( p \) of the accretion rate (\( \dot{M}_{\text{acc}} \propto r^p \)). We further test if our theoretical models can match the state dependant and angle dependant nature of the accretion disk winds. The results of our study are listed below:

- The cold solutions, which are solely driven by the magnetic acceleration, produce very narrow regions of detectable wind and from the outer parts (\( \geq 2.51 \times 10^3 r_g \)) of the accretion disk. In addition, the cold MHD winds have lower density (\( \log n_H < 9.9 \)) than what observations predict. The winds were found to be equatorial, within \( i \sim 30^\circ \) of the accretion disk surface.
- We realised that we need high values of \( p(>0.04) \) to reproduce winds that can match observations. However \( p \) cannot be increased to desirable values in the framework of the cold MHD solutions. We definitely need warm MHD solutions to explain the observational results. In the warm MHD solutions, some extra heating at the disk surface causes a larger mass loading at the base of the outflow, which is then magnetically accelerated to form a denser wind. We speculate that the aforementioned heating may be due to the illuminating SED, particularly in the Soft state.
- In the Soft state, our densest warm MHD solution predicts a wind at \( 7.05 \times 10^2 r_g \) with a density of \( \log n_H \approx 11.1 \). The densest part of the wind \( (\log n_H > 8) \) still remains equatorial - within \( i \sim 30^\circ \) of the accretion disk. The values of the physical parameters are consistent with some of the observed winds in BHBs. However, there are some other extreme observations (e.g of GRO J1655-40 Miller et al. 2008) which require a denser wind which is at a smaller distance to the black hole. From our work we understand what kind of MHD solutions can reproduce such extreme winds - warm MHD solutions with \( p \approx 0.5 \). It was beyond the scope of this paper to produce those particular solutions. However, we will generate and report such solutions in our future publications where we will attempt to reproduce spectra of BHB winds of different kinds.
- The outflow illuminated by a Hard SED will not produce detectable wind because (i) the allowed region of the winds is smaller (compared to the Soft SED case) and (b) the wind region falls within the thermodynamically unstable range of \( \log \xi \) and hence unlikely to be detected. Further in the absence of favourable illumination, it is likely that the Hard state will have an associated cold outflow, which is incapable of producing the usually observed winds. When these two aspects are considered together, we realise that it is impossible to ever produce a wind in the canonical Hard state.

Thus in the framework of MHD outflows we can satisfy the observed trends reported in Ponti et al. (2012, and references therein) that - (a) winds are observed in the Soft states (and not expected in the Hard state) of the BHB outbursts and (b) accretion disk winds in BHBs are equatorial. We have been able to reproduce the expected values (consistent with observations) of distance, density and velocity for the average winds in BHBs. For the extremely dense (and hence at small distances from the black hole) winds our rigorous analysis was capable of pointing to the kind of accretion disks which will be able to reproduce them.

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